ENGINEERING EXPERIMENT STATION

THE EFFECT OF MATERIAL PROPERTIES ON
MATERIALS HANDLING PROCESSES

by

R. W. Christensen, R. W. Heins,
W. Babcock and R. Tonn

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The Effects of Material Properties on Materials Handling Processes

Semiannual Technical Report

R. W. Christensen, R. W. Heins, W. Babcock and R. Tons.

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In order to achieve a better understanding of the fundamental aspects
of materials handling by a conveyor system, a model system is being con-
structed. Among the major problems to be dealt with are those which
result from scaling down from the full size unit. A statistical experimen-
tal design has been set up to evaluate the actions and interactions between
the variables. This should lead to a minimum amount of experimental tests.
A number of physical properties of a limestone sample obtained from a
tunnel boring machine have been run and reported.

Model conveyor

Statistical experimental design

Particle size distribution

Particle shape

Particle shear strength

SIX MONTH TECHNICAL REPORT

AUGUST 1971

THE EFFECT OF MATERIAL PROPERTIES ON MATERIALS HANDLING PROCESSES

by

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SUMMARY

We believe that in order to achieve the materials handling capabilities required, a better understanding of the fundamental aspects of the materials-system interface and interactions must be obtained. In particular, we are interested in the effect of the physical properties of excavated material on the handling system. The selection of equipment based on experience, tradition or intuition is no longer valid but must be based in part on an analysis of the physical properties of the material to be handled. Since these materials are man-made, it should be possible to change them if such changes prove beneficial to their handleability.

For the purpose of this investigation, a model belt conveyor system has been selected for study and is being constructed. The belt conveyor system is the most often used system for bulk material handling problems. By model or scaled system, we mean one that is about one-third the standard full size machine (24 inches wide). Our choice is based largely on the problems associated with acquisition, storage and utilization of a bulk sample if a full size system were adopted. Scaling, however, leads to many other problems which remain to be solved.

A discussion is presented on the experimental design approach to experimentation in which are listed what we consider some of the more important variables. Using this approach, actions and interactions between variables can be isolated and determined with a minimum amount of experimentation.

Finally, a sample of excavated material has been obtained from an underground construction project in Milwaukee, Wisconsin. The machine was cutting through a shallow limestone and shale horizon, and approximately 1,000 pounds of material was diverted as a sample. A number of physical property tests have been run and are reported here.

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INTRODUCTION

The advent of large diameter tunneling machines marks a new era in tunneling practice. While these machines are capable of excavating hard rock rapidly and continuously, new designs of even greater capacity are being developed and tested. Rapid excavation underground, at rates never before dreamed of, appears to be just around the corner. For example, a revolutionary piece of equipment in prototype form has undergone tests by the military, and it has the theoretical potential of producing 150,000 cubic yards of material per hour (1). This is an astounding rate of production of material, and all of it must be moved from the machine efficiently and without delay. Hence, the problem of materials handling associated with rapid excavation arises.

The present tunneling machines are a result of the practice and expertise developed in the early 1950's by the coal producers. In need of high productivity per man hour, these companies fostered the development of continuous mining machines which literally ripped the coal from the face. These machines were also equipped with loading devices that moved the material away from the face and onto a conveyor to an extensible belt or to a shuttle car behind the miner. Essentially, these same machines from the coal mines were then used in soft rock, e.g., potash, with good success.

Having been shown that continuous mining equipment was practical, the manufacturers began working on systems where rock materials with higher compressive strengths could be mined continuously. The continuous

excavator represents a breakthrough in that hard rock (compressive strength in excess of 25,000 psi) can be excavated by machine, and this removes the constraints of the cyclic drill-blast method.

The fact that rock is fragmented by these machines is largely a function of the speed of the cutting head and the rate of the machine's advance. A number of cutter designs have been proposed and tried on actual excavations. These designs have drawn fairly heavily on the technological advances made in drilling oil wells. The particle size distribution and particle shape of an excavated material are, in part, dependent on the type of cutter used as well as the relative strength of the material in place. The linear cutter or disk cutter as applied in soft to medium hard formations produces larger particles or chips which tend to be plate-like in shape. In contrast, the tungsten carbide insert cutter which is used in very hard formation tends to produce fine chips of more equal dimensions. Thus, it can be seen that both cutter design and rock strength influence chip shape and size distribution and could become controllable variables if it were shown that these properties had an important influence on the materials handling problem.

While it is quite speculative at this point, it is the purpose of this research to analyze and attempt to determine the influence of such properties as particle shape, particle size distribution, angle of internal friction and moisture content on the way these materials are handled on a conveyor belt. This could result in three approaches toward a solution of the problem. First, the materials handling system might be designed around those properties and variables which are shown to be important in the handling process. Secondly, most of the variables mentioned are controllable and might be changed, if such changes make the handling problem any easier. As a third alternative, a combination of handling system design and materials property changes could be used.

EQUIPMENT DESIGN

Before attempting the design of a belt conveyor system, the effects of the characteristics of the material to be handled must be considered. In terms of the performance of a belt conveyor system, the following material characteristics must be considered (7):

Angle of Repose - The angle which the surface of a normal, freely formed pile makes to the horizontal.

Angle of Surcharge - The angle to the horizontal which the surface of the material assumes while the material is at rest on a moving conveyor belt.

Flowability - The combined effect of angle of repose and angle of surcharge on the behavior of the material on a belt conveyor. Table 1 illustrates the flowability for a range of material types.

The material characteristics defined above are, in reality, manifestations of more basic material properties as well as the slope, speed and cross sectional configuration and movement of the conveyor belt. The important physical properties which affect materials handling on a conveyor belt are particle size distribution, shape of particles, abrasiveness, density, internal friction and cohesive properties of the material. Thus, the belt conveyor test section for this study must be designed such that the effects of these material characteristics on the performance of a belt conveyor system can be properly assessed.

There are two possible approaches that can be taken in designing the test section: (1) A full-scale belt conveyor system could be used, or (2) a miniature model could be constructed with all factors involved in the conveyor system scaled appropriately.

The decision to construct a scaled or model conveyor system for experimentation was finally reached after weighing the advantages and disadvantages of the full size system against the scaled version. While the full sized version offered the advantage of obtaining easily correlated

TABLE 1 FLOWABILITY-ANGLE OF SURCHARGE-ANGLE OF REPOSE (2)

Very Free Flowing 1°	Free Flowing 2°	Average Flowing 3°		Sluggish 4°	Profile on Flat Belt
5° Angle of Surcharge	10° Angle of Surcharge	20° Angle of Surcharge	25° Angle of Surcharge	30° Angle of Surcharge	Angle of Surcharge
5°	10°	20°	25°	30°	α
0°-20° Angle of Repose	20°-30° Angle of Repose	30°-35° Angle of Repose	35°-40° Angle of Repose	40°-Up Angle of Repose	Other Angles of Repose

MATERIAL CHARACTERISTICS

Very Free Flowing 1°	Free Flowing 2°	Average Flowing 3°	Sluggish 4°	Profile on Flat Belt
Uniform size, very small rounded, dry polished particle, either very wet or very dry, such as dry silica sand, cement, wet concrete, etc.	Rounded, dry polished particles, of medium weight such as whole grain and beans.	Irregular, granular or lumpy materials of medium weight such as anthracite coal, cottonseed meal, clay, etc.	Typical common materials such as bituminous coal, stone, most ores, etc.	Irregular, stringy, fibrous, interlocking materials, such as wood chips, bagasse, tempered foundry sand, etc. May include any characteristic shown in designations 1 thru 4.

empirical data, building and operating such a machine was prohibitive, and in general would be unsuitable for our purpose. Also, being charged with using representative materials in the study presented the problem of obtaining and handling the large volume of materials required. The smaller system overcomes the physical size problems as a whole, but presents new problems within the conveyor itself. Parts for such a small piece of equipment (belt width of 8 inches or less is not readily available) and required clearances within the machine do not diminish proportionately with smaller overall size.

To carry out the intended studies on the conveyor system, a small scale compact, versatile, lightweight piece of equipment is necessary. We have found that many of these attributes are inherently contradictory. Compactness and versatility offer the greatest challenge. In order to meet the requirements of the experimental design, the various components of the conveyor must be fully adjustable.

Design and development to date have centered on the idler assembly. Study and trial fabrication convinced us that making an assembly that is completely adjustable within certain limits will cause more design and fabrication problems than it is worth, requiring special parts made by custom casting, machining, or stamping. This last point in itself is a serious shortcoming with regard to time and cost. A simpler design, fashioned after full scale troughing idlers seems to be more favorable. This will consist of sets of rigid brackets that can be easily interchanged to vary the troughing angles. The brackets will be bolted to the frame so that changing the angle will involve changing the brackets on the outer idlers, using the same rolls, shafts and bearings. This design offers a construction advantage in that only cold bending of steel flat stock and welding will be required for fabrication. We feel that this design will offer enough flexibility for the experiment with a minimum expenditure. Figure 1 is a drawing (to scale) of the idler design which is being constructed.

As another practical advantage, the bracket design shown on Figure 1 will allow us to keep the transverse roller spacing to a minimum. One of
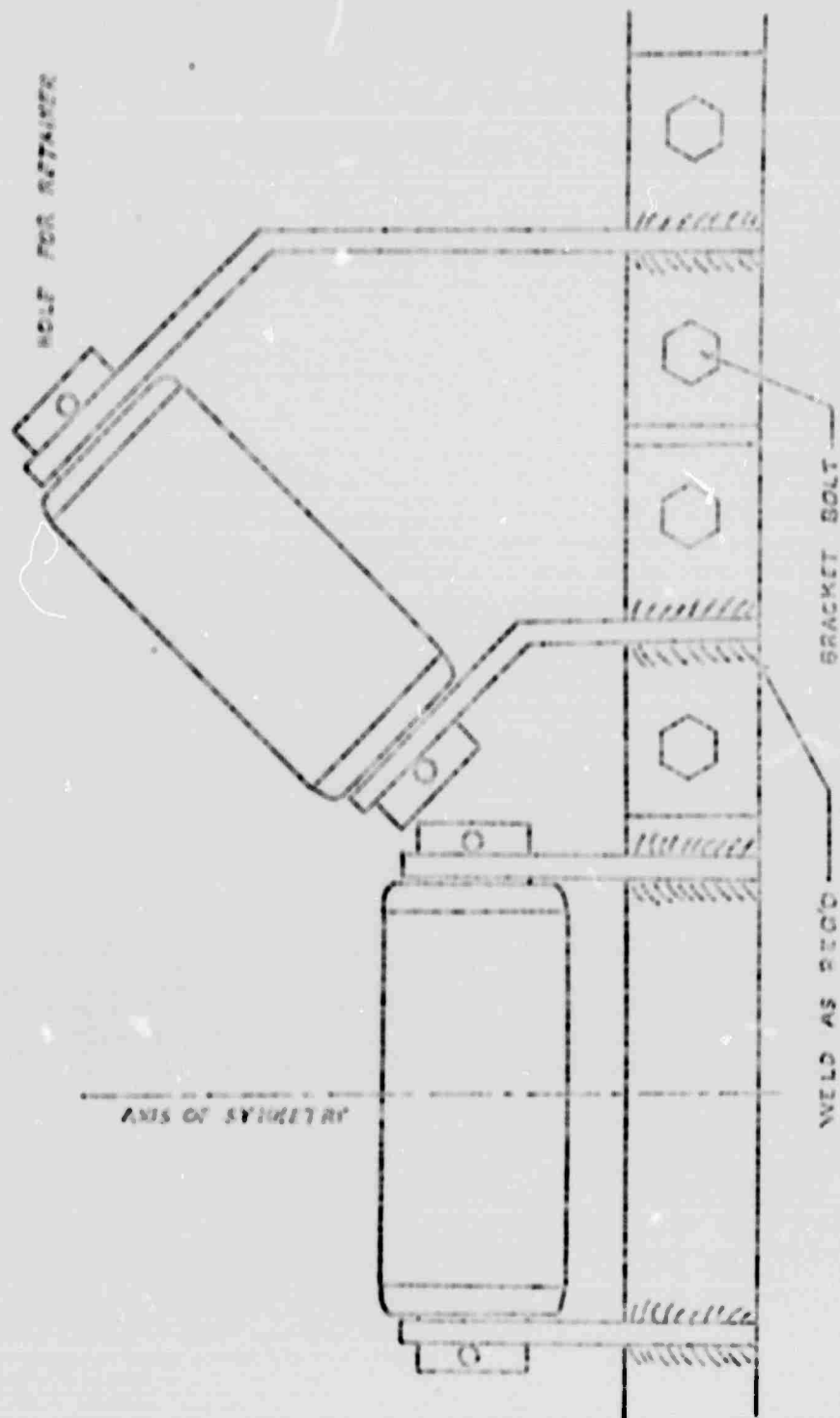
TYPICAL IDLER ASSEMBLY

HOLE FOR RETAINER

BRACKET BOLT

WELD AS REQ'D

AXIS OF SYMMETRY

Note:

Idler roll and shaft drawn to scale

Figure 1

the shortcomings of the adjustable assembly is the increased unsupported distance between rollers in the idler assembly. Using a simple hinged support on the inside resulted in about 1/3 of the belt being unsupported when in the flat position. This would surely have been a problem considering the flexibility required in the belting for it to trough.

At the present time, we are testing a plastic roll end bearing which is available at low cost for use in the idler design. The plastic is teflon added to either delrin or celcon. Teflon, being a naturally lubricating substance with good wear characteristics should make this plastic bearing usable. These bearings are placed in the end of a hollow tube cut to the desired length for each roller of the idler. The shaft of each roller is cut to length and the roller is held on the shaft using shaft clips which are available. If the tests of the plastic roll end bearing are satisfactory, we should be able to construct a lightweight idler assembly where the mounting brackets can be easily interchanged to obtain different troughing angles.

As an alternative to the plastic roller and bearing, an idler assembly using sealed ball bearings is also being constructed. However, this system offers the disadvantages of greater weight, requires machining in construction, and each ball bearing costs about three times the plastic bearing.

In the design of the model conveyor system, the scaling factors for the machine and the material must be determined. For the machine itself, scaling problems arise concerning the appropriate belt flexibility and idler spacing to use in relation to the material load being carried by the belt. Our studies indicate that, for a given material, the controlling factor in determining the behavior of the material on the conveyor is the vertical acceleration experienced by the material as it travels along the belt. The problem, then, is to design the model conveyor in such a way that the vertical acceleration pattern imparted to the material by the test conveyor section is similar to that which it would experience on a full sized conveyor.

The vertical acceleration imparted by a conveyor to the material being handled is a function of belt speed and the deformed shape of the belt under

load. The deformed shape of the belt is, in turn, a function of the weight of material being carried, idler spacing, belt flexibility and belt tension. In order to model the full scale operation as closely as possible, it is anticipated that belt speeds used in the tests will be similar to those used with full sized conveyors. Therefore, since the load of the material being carried on the model conveyor will be a small fraction of that carried by a full sized conveyor, it is apparent that the belt used on the model conveyor will have to be considerably more flexible than full sized belts. Furthermore, idler spacing may have to be reduced in the test section because of space limitations; this will also require greater belt flexibility in order to keep the deformed shape of the belt similar to that of a full sized conveyor. A reduction in belt tension can also be used to achieve the same purpose. By appropriate scaling of the various factors involved, it should be possible to model the material handling characteristics with a small scale version of the conveyor system.

For the material, cohesion, abrasiveness, and particle size present the major potential scaling problems; the angle of repose (or angle of internal friction) does not depend upon scale. Since the materials being considered in this study are granular, most of the cohesive properties that may be present would be due to capillary effects, although some cohesion due to electrostatic effects may be present in the very fine-grained fraction. It appears doubtful that cohesion, whether due to capillary or electrostatic effects, will be present to any significant degree in either the full sized or the model conveyor systems; capillary cohesion will probably be destroyed by disturbances to the material during the handling process and cohesion due to electrostatic attraction would be present in only the very fine-grained fraction which represents only 5-10 percent of the total sample.

Abrasive wear on the conveyor belt appears to be a difficult factor to scale. Experience with full sized conveyor systems indicates that a majority of belt wear takes place upon impact of the material as it is being

transferred onto the belt. Some additional wear may occur anywhere there is sliding of the material relative to the belt. In either case, the amount of wear is a function of the weight of material involved and the wearing qualities of the belt. It appears to be impractical to modify the wearing qualities of the belt to account for the reduction in the weight of material in the model system. On the other hand, it should be possible to assess belt wear for various test conditions and materials on a relative scale, even though the amount of wear will not be the same as in the full sized system.

The particle size distribution of the material must also be appropriately scaled for the model system. Particle size distribution can be expected to influence such factors as angle of surcharge, loss of material from the belt during handling and the force of impact when the material is transferred onto the belt. To be strictly correct, the entire particle size distribution should be altered in accordance with the reduction in belt width, and any differences in the transfer operation between the full sized conveyor and the model conveyor to properly account for loss of material during handling and impact force. However, this would also alter the angle of surcharge and the amount of cohesion present in the sample. Therefore, as a first approximation, it is planned to merely eliminate the larger sized particles while keeping the remainder of the particle size distribution unchanged. The approach to be followed will be to maintain a constant ratio of maximum particle size to belt width. For example, if the maximum particle size to be carried on a 24-inch belt is 3 inches, a maximum particle size of 1 inch would be used on an 8-inch belt. This method of scaling should eliminate excessive loss of material from the belt without introducing undesirable changes in the fundamental material properties.

EXPERIMENTAL DESIGN

A tentative fractional factorial design has been developed for conducting the experimental investigation. This program is very flexible and variables

can be added or deleted as necessary during the testing program. Regardless of the number of important variables that are finally formed in the testing program, this method of experimental design will optimize the amount of significant data obtained from a given number of experimental runs. The following material is based largely on the lectures and notes of Professors S. M. Wu and W. W. Hunter (3) at the University of Wisconsin.

Variables Being Considered

The following list of variables is considered tentative as some may have to be added or deleted as testing progresses. The equipment variables that are being considered, but not limited to, are:

g_1 = belt speed

g_2 = belt inclination

g_3 = change in inclination

g_4 = cross section configuration of conveyor bed

g_5 = belt material (coefficient of friction)

g_6 = idler spacing

g_7 = belt tension

$\left\{ \begin{array}{l} \text{longitudinal} \\ \text{configuration} \\ \text{of conveyor bed} \end{array} \right.$

The material variables that are being considered, but again not limited to, are:

q_1 = particle size distribution

q_2 = particle shape

q_3 = angle of internal friction

q_4 = moisture content

The total muck removal rate (V) is a function of the equipment and material variables:

$$V = f(g_1, g_2, g_3, g_4, g_5, g_6, g_7, q_1, q_2, q_3, q_4)$$

A general procedure of setting up the factorial and fractional-factorial designs and of computing the results will be shown. The description and

discussion of the method will be limited, though a thorough derivation is necessary for complete understanding.

The following design procedure deals with determining which variables are the most significant among the 7 equipment variables by running 2 sets of 8 tests. A similar design table can be constructed for determining the most significant variable or variables for total muck removal rate (v) by running 2 sets of 16 tests with 11 variables. These 11 variables will be made up of the 7 equipment variables and 4 material variables.

Procedure

We begin by choosing a high and low value for each test variable (since we will be using a two-level factorial or fractional factorial design). These values can be chosen from design manuals, manufacturing manuals, or from experimental models. Careful consideration should be used in selection since a good representation of high and low values will reduce the number of tests to be run. The coding equation or transforming equation used to reduce initial values to coded values of (-1) for low level and (+1) for high level is:

$$X = \frac{\text{level of variable - midvalue of variable}}{\text{unit of change}}$$

After initial values have been assumed, we can set up our factorial or fractional factorial design tables. For example, let us assume a fractional design of 2^{7-4}. The notation 2^{7-4} tells us that each variable is studied at two levels, seven test variables are being studied, four "new" variables have been added to an original 2^3 factorial design. The number of tests to be run in this design is $2^{7-4} = 2^3 = 8$. Note: A factorial design for seven variables would be $2^7 = 128$ tests which is far greater than the 8 tests we will use.

The advantage of fractional factorial designs over factorial designs is that the same number of tests (8) can be made for 7 variables as can be

made for the 3 variables in the factorial design. The data, however, is not pure as in the factorial design and involves interactions as can be seen by the design. Therefore, what one gains in the number of runs, one loses in confounding (or interaction effects).

DESIGN TABLE OF EQUIPMENT VARIABLES

Test Variable Trial No.	x_1 1	x_2 2	x_3 3	x_4 4 1·2·3	x_5 5 1·2	x_6 6 1·3	x_7 7 2·3	Results Y
1	-1	-1	-1	-1	+1	+1	+1	10
2	+1	-1	-1	+1	-1	-1	+1	20
3	-1	+1	-1	+1	-1	+1	-1	5
4	+1	+1	-1	-1	+1	-1	-1	30
5	-1	-1	+1	+1	+1	-1	-1	15
6	+1	-1	+1	-1	-1	+1	-1	25
7	-1	+1	+1	-1	-1	-1	+1	0
8	+1	+1	+1	+1	+1	+1	+1	40

Let us consider the consequences of interactions being present. While estimating the average effect or importance of a test variable, of say test variable 5, we must also include the interaction effects of test variables 1 and 2. It is important to know exactly how the average effects are confounded with interaction effects; therefore, we will construct a defining relation from which the confounding pattern for the design will be determined. The defining relation then is the key which tells us which interactions are confounded with which average effect. We can write down the generators of a design since these are the relations from which we generated (or constructed) the design. A generator is an identity column of all (+1) values. An example of a generator is: $I = 4 \cdot 123$. Since $123 = 4$, then $4 \times 4 = 4^2$ which yields an identity column of (+1) values for column x_4 because all values are squared.

GENERATORS

$$I = \underline{123} \cdot \underline{4}$$
$$I = \underline{12} \cdot \underline{5}$$
$$I = \underline{13} \cdot \underline{6}$$
$$I = \underline{23} \cdot \underline{7}$$

Next, the defining relation is composed of the generators just described and their products.

DEFINING RELATION $I = \underline{125} = \underline{126} = \underline{1234} = \underline{237}$ (generators)

$= \underline{345} = \underline{246}$ (products of 2 generators at a time)

$= \underline{147} = \underline{2356}$

$= \underline{1357} = \underline{1267}$

$= \underline{1456}$ (product of 3 generators at a time)

$= \underline{3467} = \underline{2457} = \underline{567}$

$= 1234567$ (product of 4 generators at a time)

With the defining relation, we can readily determine which quantities are confounded with one another. To determine which interaction effects are confounded with which average effect of a test variable, multiply the defining relation through with each average effect to determine the confounding relationship.

Therefore, multiply the defining relation by 1, 2, 3, 4, 5 & 6, respectively.

1 = 234 = 25 = 36 = 1237 = 1345 = 1246 = 47 = 12356 = 357 = 267 = 456 = 13467 = 12457 = 1567 = 234567

2 = 134 = 15 = 1236 = 37 = 2345 = 46 = 1247 = 356 = 12357 = 167 = 12456 = 23467 = 457 = 2567 = 134567

3 = 124 = 1235 = 16 = 27 = 45 = 2346 = 1347 = 256 = 157 = 12367 = 13456 = 467 = 23457 = 3567 = 124567

4 = 123 = 1245 = 1346 = 2347 = 35 = 26 = 17 = 23456 = 13457 = 12467 = 156 = 367 = 257 = 4567 = 123567

5 = 12345 = 12 = 1356 = 2357 = 34 = 2456 = 1457 = 236 = 137 = 12567 = 146 = 34567 = 247 = 67 = 123467

6 = 12346 = 1256 = 13 = 2367 = 3456 = 24 = 1467 = 235 = 13567 = 127 = 145 = 347 = 24567 = 57 = 123457

7 = 12347 = 1257 = 1367 = 23 = 3457 = 2467 = 14 = 23567 = 135 = 126 = 14567 = 346 = 245 = 56 = 123456

One important property of the design in the confounding pattern is that no average effect is confounded with any other average effect. Also, it is sensible to adopt as a working hypothesis that three factor and higher-order interactions are negligible and can therefore be neglected. However, one should always attempt to check this assumption later on in the investigation. Therefore, we will only consider average effects and two factor interactions.

The next step is to calculate the average effects using equation $E_j = 1/N/2 \sum_{j=1}^{N} (Q_j)(j)$ where Q_j is test result column times test variable j column and n = number of tests. $E_j = 1/4 \sum_{j=1}^{8} (Q_j)(j)$

For example, from the design table:

$$E_1 = \frac{(-1)(10) + (+1)(20) + (-1)(5) + (+1)(30) + (-1)(15) + (+1)(25) + 1(-1)(0)}{4}$$

$$+ \frac{(+1)(40)}{4} = \frac{-10 + 20 - 5 + 30 - 15 + 25 + 40}{4} = \frac{85}{4} = +21.25$$

This is not the pure average effect because of confounding, therefore $1 + 25 + 36 + 47 = E_1 = +21.25$.

Once these average effects have been calculated for all 7 columns, the results can be interpreted by observation to see where possible relationships might exist between test variables.

Next, these average effects can be untangled from the second order interaction effects by completely redoing what we have done so far except switch all of the signs of all elements of the previous design matrix (from + to – and – to +) and rerunning these 8 tests (for a total of 16 tests). The resulting confounding relation is:

$$
\begin{aligned}
1 &= -25 = -36 = -47 \\
2 &= -15 = -16 = -37 \\
3 &= -16 = -45 = -27 \\
4 &= -35 = -26 = -17 \quad \text{Second order interactions} \\
5 &= -17 = -34 = -67 \quad \text{only.} \\
6 &= -14 = -24 = -57 \\
7 &= -23 = -14 = -56
\end{aligned}
$$

Calculate average effects on these 8 tests by the previously stated method for the average effects of all 7 columns. The true (clean) average effect can be gotten by summing the average effects from each set of 8 tests and dividing by 2 (the interactions then cancel out). For example, for column 1:

$$(1 + 25 + 36 + 47) + (1 - 25 - 36 - 47) = \frac{2}{2} = 1$$

The string of two-factor interactions can be found by subtracting the 2 runs and dividing by 2 (average effects cancel out). For example, for column 1:

$$\frac{(1 + 25 + 36 + 47) - (1 - 25 - 36 - 47)}{2} = \frac{+2(25 + 36 + 47)}{2} = 25 + 36 + 47$$

The remaining and most interesting step is to evaluate the data that has just been collected. Often the resulting data will allow a two-way table explanation of the interaction effects often allowing easy interpretation of results. Once these results have been evaluated, additional tests can be run to verify the interpretations for accuracy.

Optimization of testing conditions could be found by the Response Surfaces Method, but probably will not be required because of the limited number of variations possible in a test conveyor system.

PHYSICAL PROPERTY DETERMINATIONS OF EXCAVATED MATERIAL

A sample consisting of approximately 1,000 pounds of material was obtained from a tunnel project in Milwaukee, Wisconsin. The tunneling machine was a Jarva unit drilling an eleven foot diameter interception sewer tunnel. The observation of the tunneling operation enabled us to ascertain first hand the rate of muck production, the essential characteristics of the mined material, and the method of material handling used on a typical job.

A visual inspection of the sample showed that the particles were, for the most part, plate shaped with a maximum size of approximately 3 inches

and grading down to extremely fine rock flour. The material was moist when obtained from the tunnel, but the moisture content in the as-received condition is not necessarily the natural moisture content of the material as it comes off the working face since the environment of the tunnel during the boring operation is quite damp. Furthermore, water is sometimes added to the bulk material to reduce dusting. Therefore, no attempt was made to preserve or measure the moisture content of the sample in the as-received condition.

After air-drying for several weeks, one-half of the sample was sized on a Gilson shaker over a size range from 1-1/2 inches down to 200 mesh. The minus 200 mesh material was sized by the hydrometer method. Figure 2 shows a plot of the size range of this material. The material appears to be rather well-graded, that is, nearly equal amounts of all particle sizes at least in the sizes down to 200 mesh size material. The lowest size determined was about 1.2 microns.

The specific gravity was determined to be 2.81 based on a test run in accordance with ASTM Designation D854-58 (5). This would indicate the material is probably a dolomitic limestone.

The rest of the tests were run on minus 4 mesh material following either ASTM procedures (5) or the procedures as given by Friaque and Marsaccini (6). Samples used in the tests were blended in proportion to the size analysis.

The maximum and minimum bulk densities were found to be 140.7 and 95.7 pounds per cubic foot, respectively, both being obtained on an air dried sample. The minimum bulk density was determined by spooning the material into a 1/30 cubic foot mold. The maximum bulk density in this test was achieved by compacting seven layers with 50 blows each on the Proctor machine. Vibration equipment was unavailable at the time of the test, and some destruction of larger grains was noted due to the compacting procedure.

Three direct shear tests were run using different normal stresses on each run. Figure 3 is a plot showing the results of these tests. The

GRAIN SIZE DISTRIBUTION CURVE

MILWAUKEE TUNNEL MATERIAL

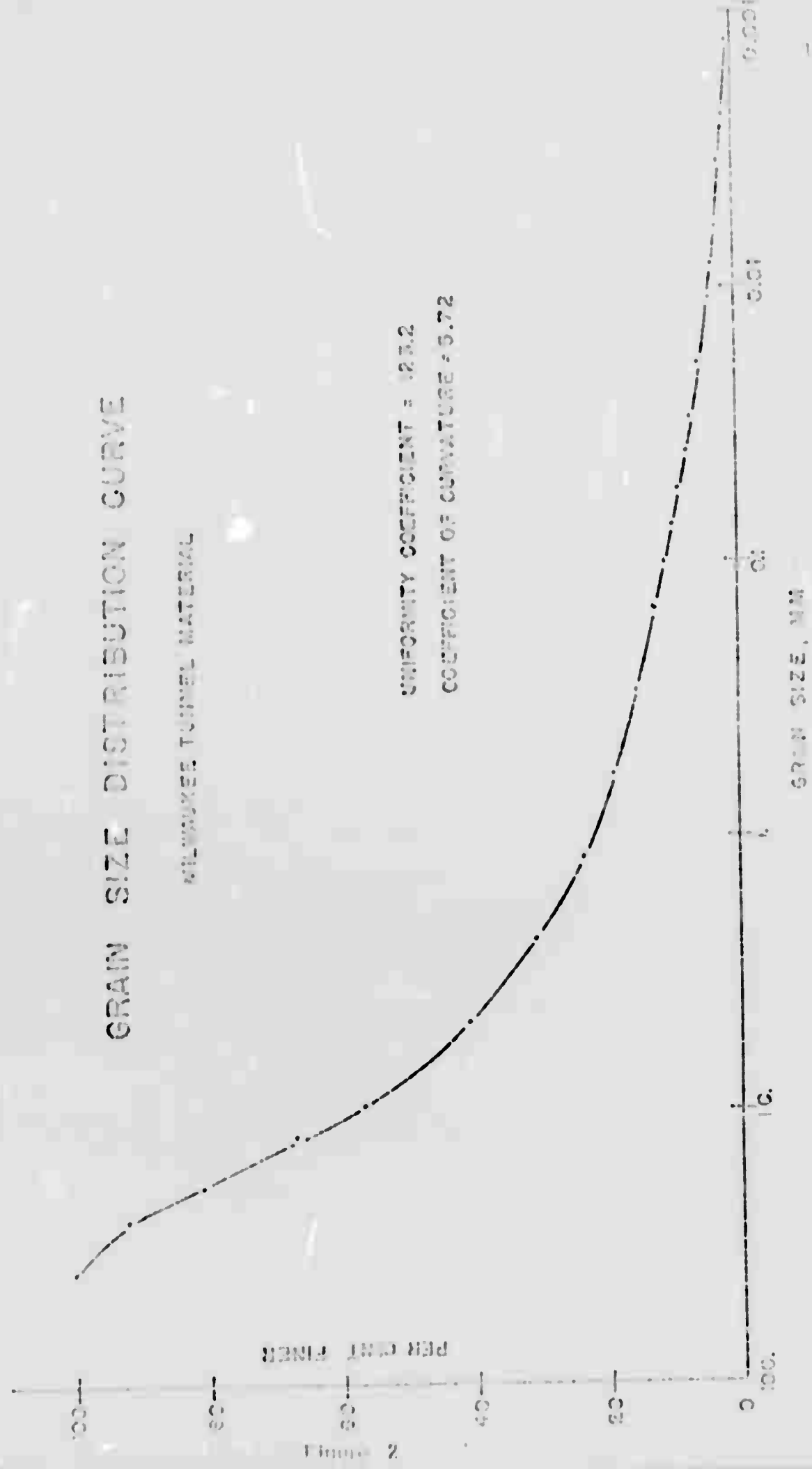UNIFORMITY COEFFICIENT = 123.2

COEFFICIENT OF CURVATURE = 5.72

PER CENT FINER

GRAIN SIZE, MM

Figure 2

STRESS-STRAIN

STRESS CONTROLLED DIRECT SHEAR TEST

MILWAUKEE TUNNEL MATERIAL

$\sigma_n = 14.26$ psi
FAILURE AT $\sigma_v = 18.01$ psi

$\sigma_n = 9.13$ psi
FAILURE AT $\sigma_v = 12.93$ psi

$\sigma_n = 5.26$ psi
FAILURE AT $\sigma_v = 7.06$ psi

STRESS psi

STRAIN $\times$ 10^3

Figure 3

18

MOHR DIAGRAM
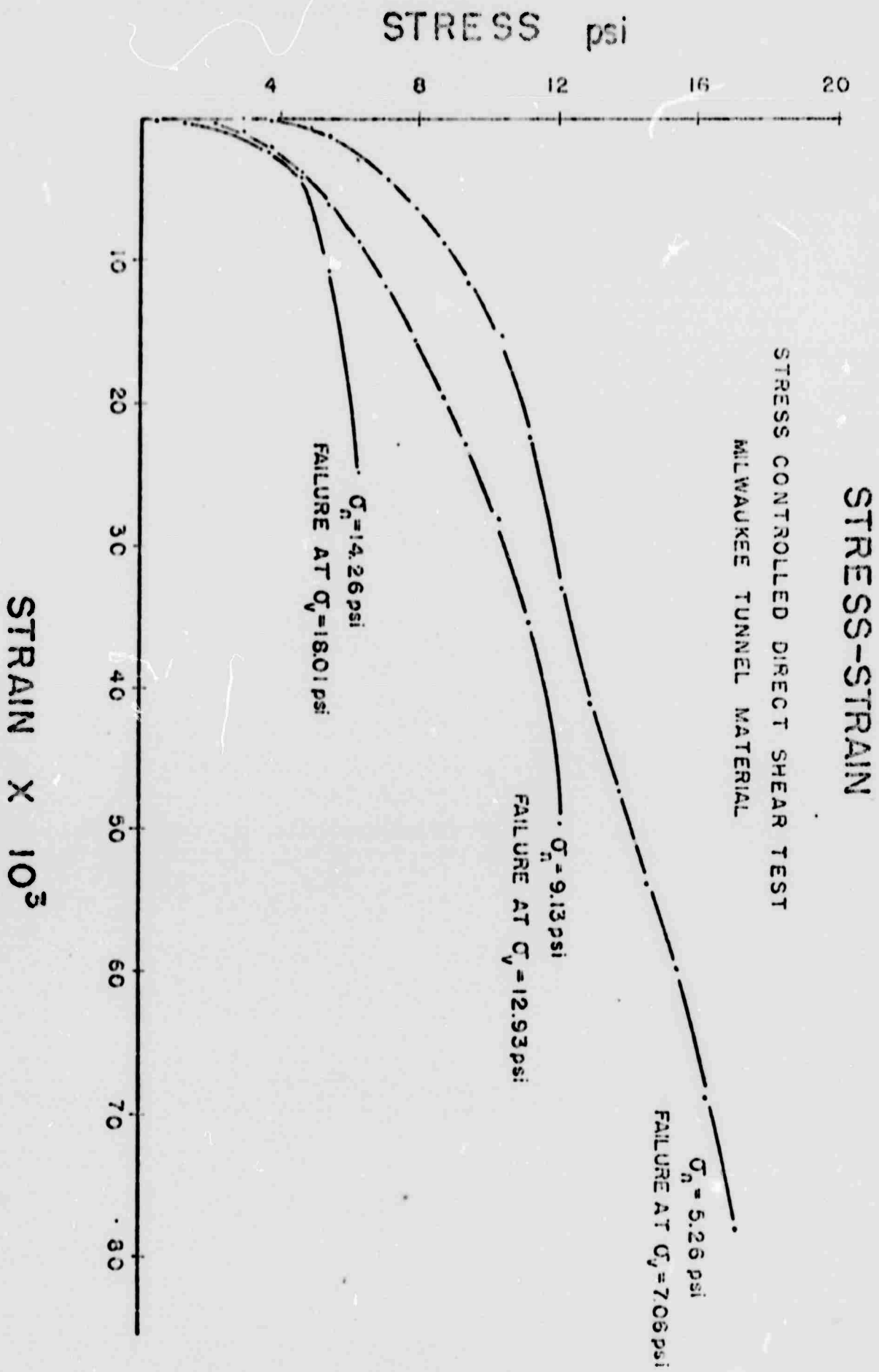MILWAUKEE TUNNEL MATERIAL
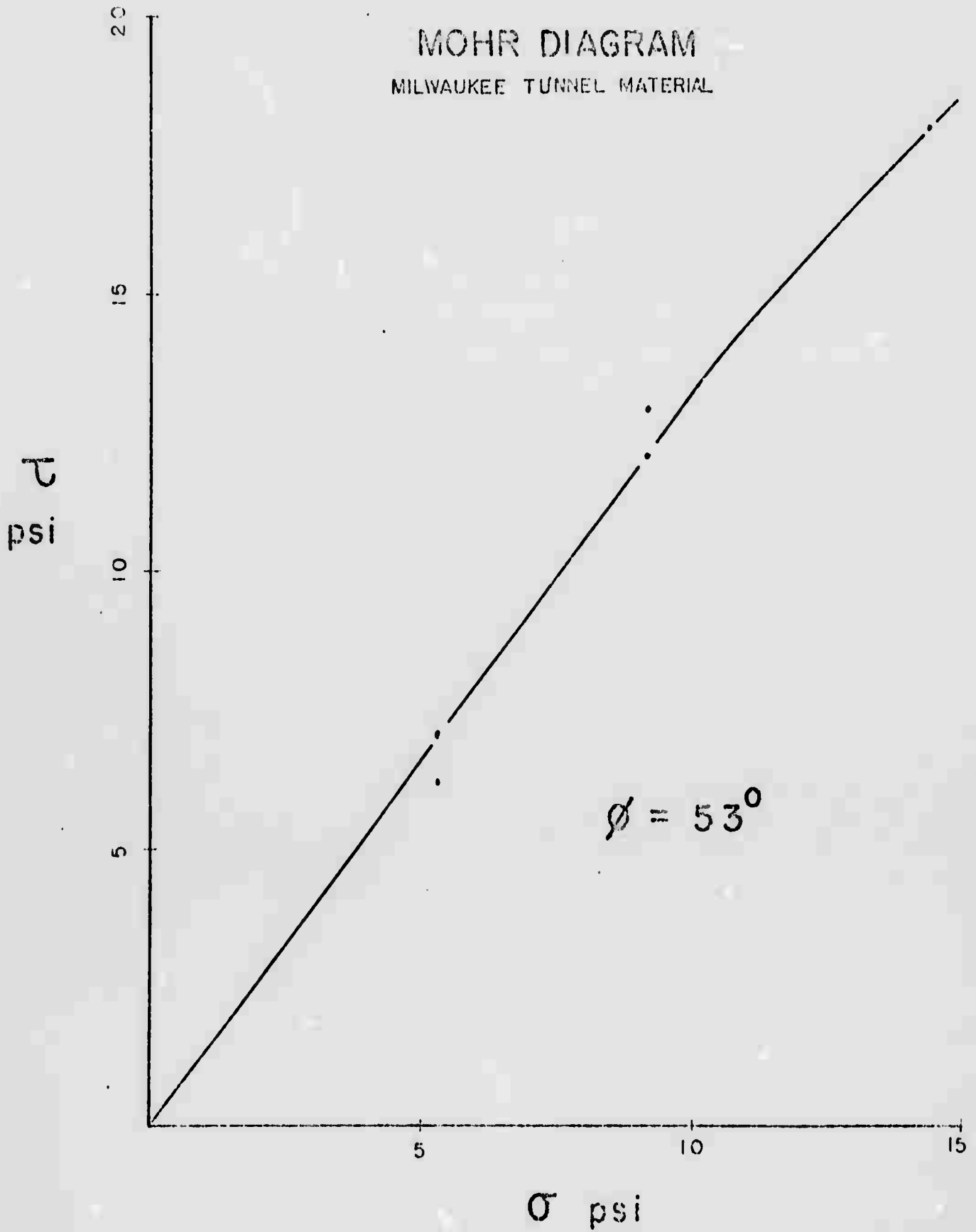
$\emptyset = 53^{0}$

τ psi

σ psi

Figure 4

The machine was under stress control and the sample was in an air-dried state. Figure 4 is a plot of the normal stress vs. shear stress, and the angle of internal friction, $\emptyset$, was 53°.

Some difficulty was experienced in determining the angle of repose. The material tended to dome and rat hole in the funnel. In spite of the difficulties, the angle of repose was found to be 45°.

In summary, the material being studied had the following physical characteristics or properties:

> Specific gravity 2.81 (run on minus 200 mesh)
> Hygroscopic moisture content < 0.5%
> Angle of internal friction, $\emptyset$ 53°
> Angle of repose, 45°
> Bulk density:
>   maximum - 140.7 pounds per cubic foot
>   minimum - 95.7 pounds per cubic foot

Additional tests on this material are being planned.

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